DC Copper Loss

$$R_{DC} = \rho \frac{l_w}{A_w}$$

l_w ← length of winding

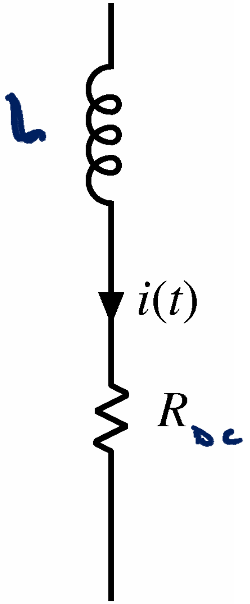
A_w ← Area of winding

ρ ↑ resistivity of copper →

$$\rho = 1.724 \times 10^{-6}\ \Omega \cdot cm \text{ @ } 25°C$$
$$2.3 \times 10^{-6}\ \Omega \cdot cm \text{ @ } 100°C$$

$$l_w = n \cdot MLT$$

MLT = "Mean length per turn"



Filter Inductor Design Constraints

① Get my designed inductance L

② Make sure inductor doesn't saturate ($I_{max} \le I_{sat}$)

$I_{max} \rightarrow$ maximum (instantaneous) current in inductor in our converter (plus some margin)

③ Minimize power loss (R_{DC} for now)

④ All windings need to fit in the core

Design Parameters

Ⓐ Core { material, B_{sat}, μ ; A_c, l_m ; MLT, W_A }

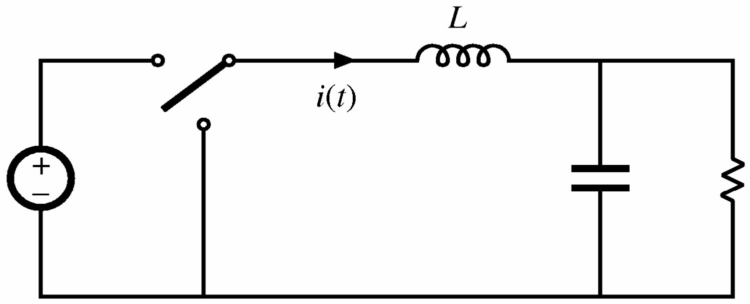
Ⓑ # of turns n

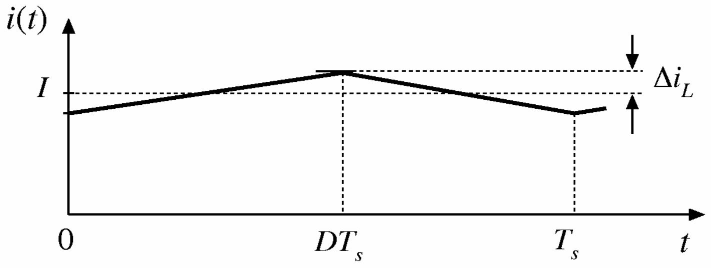
Ⓒ Air gap l_g

Ⓓ Wire area A_w

Design Goals

Example: filter inductor in CCM buck converter





① Desired inductance

$$L = \frac{\mu_0 n^2 A_c}{l_g}$$

(Assuming $\mathcal{R}_g \gg \mathcal{R}_c$)

② Prevent saturation

$$I_{max} > \frac{l_g}{n\mu_0} B_{max}$$

w/ $B_{max} < B_{sat}$ by some margin
by e.g. 10-25%

Geometrical Parameters

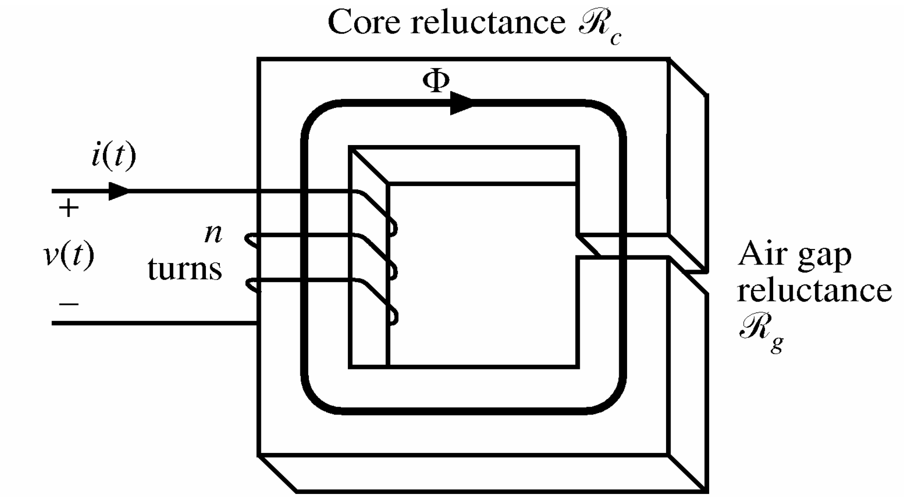
(3) Minimize Loss (R_{DC})

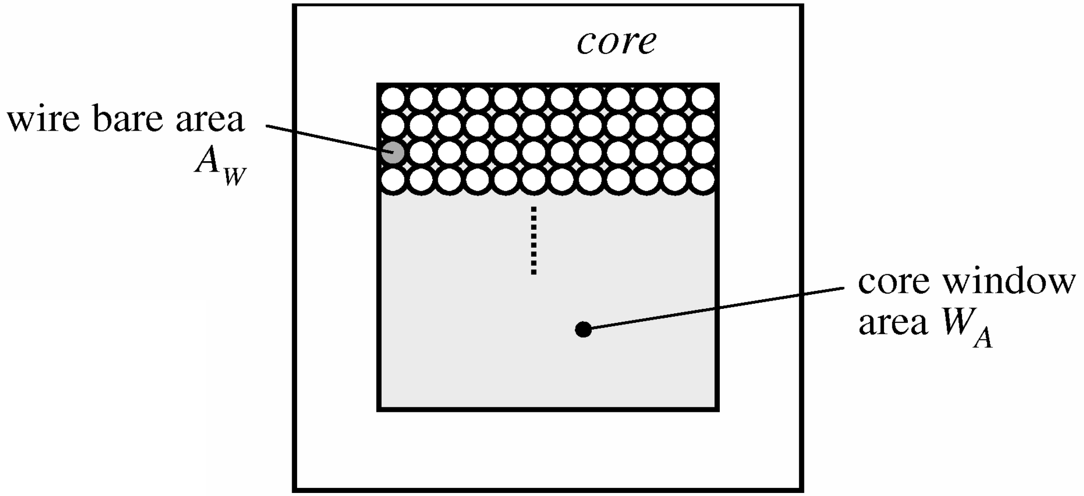
$$R_{DC} = \rho \frac{n \cdot MLT}{A_w}$$

(4) Wires need to fit

$$n A_w \le W_A K_u$$

- W_A: window Area
- K_u: "fill factor"
  - $0 \le K_u \le 1$
  - $\frac{\pi}{4}$ w/ perfect circle-to-square & no insulation
  - 0.5 for simple inductor
  - < 0.2 for HV magnetics
  - ~0.7 for foil windings





The K_g Method

① $L = \frac{\mu_0 n^2 A_c}{l_g}$

② $I_{max} \geq \frac{l_g}{n \mu_0} B_{max}$ (=)

③ $R_{DC} = \rho \frac{n \, MLT}{A_w}$

④ $A_w \leq \frac{W_A K_u}{n}$ (=)

combine ① & ② & eliminate l_g

$$I_{max} = \frac{1}{n \mu_0} B_{max} \frac{\mu_0 n^2 A_c}{L} = \frac{B_{max} n A_c}{L}$$

③ & ④ & eliminate A_w

$$R_{DC} = \rho \frac{n^2 MLT}{W_A K_u}$$

combine & eliminate n

$$I_{max}^2 = \frac{B_{max}^2 A_c^2}{L^2} \frac{R_{DC} W_A K_u}{\rho \, MLT}$$

circuit Analysis ↓ core geometry ↓

$$\frac{I_{max}^2 L^2 \rho}{B_{max}^2 R_{DC} K_u} \leq \frac{A_c^2 W_A}{MLT} = K_g \; [cm^5]$$

K_g Method

The following quantities are specified, using the units noted:

Wire resistivity	ρ	(Ω-cm)
Peak winding current	I_{max}	(A)
Inductance	L	(H)
Winding resistance	R	(Ω)
Winding fill factor	K_u	
Maximum operating flux density	B_{max}	(T)

The core dimensions are expressed in cm:

Core cross-sectional area	A_c	(cm^2)
Core window area	W_A	(cm^2)
Mean length per turn	MLT	(cm)

$$K_g \geq \frac{\rho L^2 I_{max}^2}{B_{max}^2 R K_u} 10^8 \quad (\mathrm{cm}^5)$$

$$\ell_g = \frac{\mu_0 L I_{max}^2}{B_{max}^2 A_c} 10^4 \quad (\mathrm{m})$$

$$n = \frac{L I_{max}}{B_{max} A_c} 10^4$$

$$A_W \leq \frac{K_u W_A}{n} \quad (\mathrm{cm}^2)$$

$$R = \frac{\rho n\,(MLT)}{A_w} \quad (\Omega)$$

Appendix B

D.2 EE CORE DATA

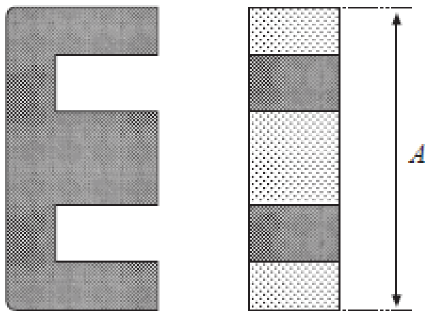


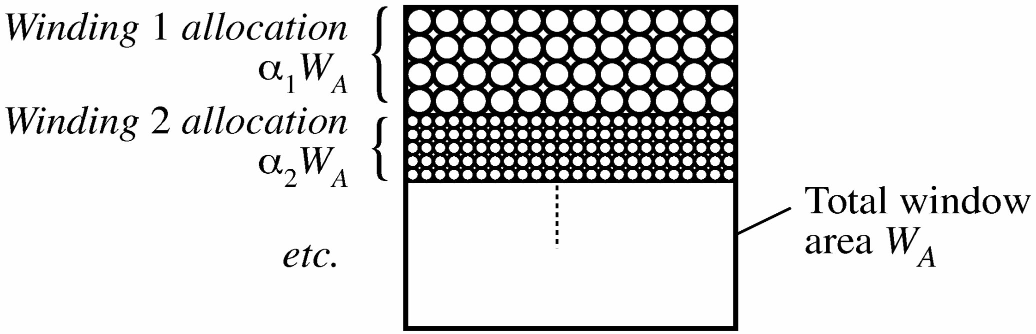
Fig. D.2

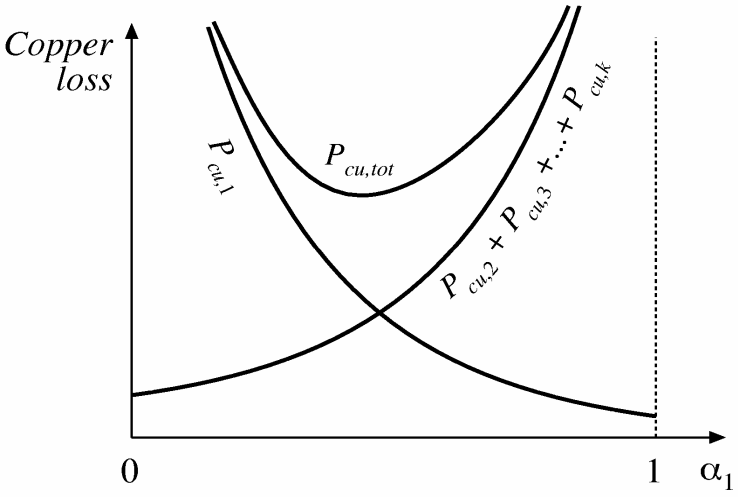
Core type (A) (mm)	Geometrical constant K_g (cm^5)	Geometrical constant K_{gfe} (cm^x)	Cross-sectional area A_c (cm^2)	Bobbin winding area W_A (cm^2)	Mean length per turn MLT (cm)	Magnetic path length ℓ_m (cm)	Core weight (g)
EE12	$0.731 \cdot 10^{-3}$	$0.458 \cdot 10^{-3}$	0.14	0.085	2.28	2.7	2.34
EE16	$2.02 \cdot 10^{-3}$	$0.842 \cdot 10^{-3}$	0.19	0.190	3.40	3.45	3.29
EE19	$4.07 \cdot 10^{-3}$	$1.3 \cdot 10^{-3}$	0.23	0.284	3.69	3.94	4.83
EE22	$8.26 \cdot 10^{-3}$	$1.8 \cdot 10^{-3}$	0.41	0.196	3.99	3.96	8.81
EE30	$85.7 \cdot 10^{-3}$	$6.7 \cdot 10^{-3}$	1.09	0.476	6.60	5.77	32.4
EE40	0.209	$11.8 \cdot 10^{-3}$	1.27	1.10	8.50	7.70	50.3
EE50	0.909	$28.4 \cdot 10^{-3}$	2.26	1.78	10.0	9.58	116
EE60	1.38	$36.4 \cdot 10^{-3}$	2.47	2.89	12.8	11.0	135
EE70/68/19	5.06	$75.9 \cdot 10^{-3}$	3.24	6.75	14.0	18.0	280

D.6 AMERICAN WIRE GAUGE DATA

AWG#	Bare area, 10^{-3} cm^2	Resistance, 10^{-6} Ω/cm	Diameter, cm
0000	1072.3	1.608	1.168
000	850.3	2.027	1.040
00	674.2	2.557	0.927
0	534.8	3.224	0.825
1	424.1	4.065	0.735
2	336.3	5.128	0.654
3	266.7	6.463	0.583
4	211.5	8.153	0.519
5	167.7	10.28	0.462
6	133.0	13.0	0.411
7	105.5	16.3	0.366
8	83.67	20.6	0.326
9	66.32	26.0	0.291
10	52.41	32.9	0.267
11	41.60	41.37	0.238
12	33.08	52.09	0.213
13	26.26	69.64	0.190
14	20.02	82.80	0.171
15	16.51	104.3	0.153
16	13.07	131.8	0.137
17	10.39	165.8	0.122
18	8.228	209.5	0.109
19	6.531	263.9	0.0948
20	5.188	332.3	0.0874
21	4.116	418.9	0.0785
22	3.243	531.4	0.0701
23	2.508	666.0	0.0632
24	2.047	842.1	0.0566
25	1.623	1062.0	0.0505
26	1.280	1345.0	0.0452
27	1.021	1687.6	0.0409
28	0.8046	2142.7	0.0366
29	0.6470	2664.3	0.0330

K_g Method: Multi-Winding Magnetics





$$0 < \alpha_j < 1$$

$$\alpha_1 + \alpha_2 + \cdots + \alpha_k = 1$$

$$\alpha_m = \frac{V_m I_m}{\sum_{n=1}^{\infty} V_j I_j}$$

Apparent power in winding j is

$$V_j I_j$$

where V_j is the rms or peak applied voltage

I_j is the rms current

Window area should be allocated according to the apparent powers of the windings